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Biomechanical Assessment of the Canadian Integrated Load Carriage System using Objective Assessment Measures

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Summary

The purpose of this study was to provide an overview of contributions by biomechanical testing to the design of the final Canadian Clothe the Soldier (CTS) load carriage (LC) system. The Load Carriage Simulator and Compliance tester were used during design of the CTS system for evaluation of: three fragmentation vests, seven Tactical Vests and three iterations of the rucksack. Test data were compared to a data pool of previously tested systems. Results indicated that the objective measures helped the design team by: 1) understanding the consequences of various design changes; 2) predicting soldiers' responses to design changes in pressure, force and relative motion; 3) comparing this system objectively to other systems; and 4) providing information quickly so that ideas could be incorporated into the next design iteration. It was concluded that objective assessments added valuable information not easily interpreted from human trials. However, objective assessments cannot replace human trials for feedback on functionality and features.

Introduction

The Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) undertook a research and development program on advanced personal load carriage systems as a part of their soldier modernization efforts. Their goal was to improve soldier's personal equipment by better integration of load carriage components and improved protection within the load carriage system for soldier safety in future conflict or peacekeeping operations. The Canadian soldier modernization program involved two components: upgrading the current soldier system under Crown acquisition project L2646 Clothe The Soldier (CTS) and developing future soldier systems under Crown project D6378 Integrative Protective Clothing and Equipment (IPCE).

The task assigned to Queen's University was to develop a cost effective, quantitative and reliable method by which various load carriage equipment designs could be evaluated and recommendations integrated into further design iterations. In this regard, Queen's joined part of a comprehensive team, led by DCIEM, that included designer/manufacturers (Pacific Saftely Products, for the load-bearing and fragmentation protective vest designs, and Ostrom Outdoors Inc., for the design of the integrated patrol pack and rucksack), human factors assessment specialists (Human Systems Inc.), and the necessary military portfolios needed to develop a new modernized CTS load carriage system. The design team was structured with DCIEM taking the lead. Prototypes and design ideas were evaluated by a series of biomechanical tests at Queen's University, and by via focus groups and field trials with soldiers at a number of military bases (Figure 1). The designer was asked to respond to the design changes needed based on either the biomechanical analysis or soldier feedback. By this model, soldier input was central to and incorporated into the design process.

Paper presented at the RTO HFM Specialists' Meeting on "Soldier Mobility: Innovations in Load Carriage System Design and Evaluation", held in Kingston, Canada, 27-29 June 2000, and published in RTO MP-056.

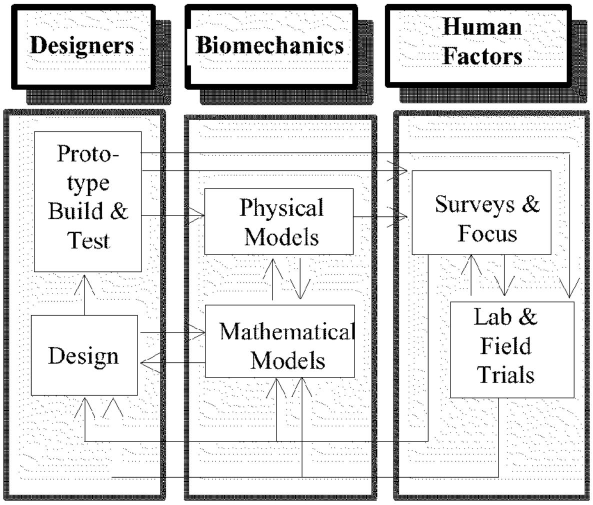

Figure 1. Model of interactions and responsibilities of DCIEM's CTS Load Carriage System Design Team.

The purpose of this paper is to provide an overview of contributions by biomechanical testing to the final Canadian CTS load carriage (LC) system design. The work plan was structured to complete the design iteration process as quickly as possible (within a year for each item), so rapid objective feedback was essential. The overall goal of the project was to conduct various biomechanical assessments of components and total LC system in order to improve design concepts through objective biomechanical assessments, comparison to a data pool of other LC systems and integration of components.

The specific purposes of the study were to use the standardized biomechanical simulations to evaluate: 1) three fragmentation vests currently in the evaluative process by the Canadian military; 2) seven webbing or load carriage vests under two conditions; with and without a fragmentation vest; and, 3) three iterations of the final CTS rucksack. In all cases, investigators gave feedback to the design team about the results of evaluations and compared the design iteration to the database of other LC systems. In addition, potential soldier discomfort concerns and compatibility problems were identified as well as possible design solutions or enhancements.

Methods

The testing program for each sub-study was selected to provide the most appropriate feedback relating to conditions of use. Two assessment tools will be described briefly as well as their test protocols.

Load Carriage Simulator. The Load Carriage Simulator was designed to capture the impact of a LC system on the human torso based on normal gait motions. It is a standardized assessment tool that allows researchers to evaluate the impact of different designs on human performance. The LC Simulator outcome measures were validated against soldiers' subjective responses and this information was reported by Bryant et al.[1, 2] It is an innovative design using a computer-controlled pneumatic system that can be programmed to walk, jog or run in a sinusoidal pattern reflecting the human gait pattern[3]. A 50th percentile anthropometrically adjusted male hard-shelled mannequin was covered with a skin analogue Bocklite™ and mounted onto a six degree of freedom AMTI load cell. The load cell, attached between a pivoting base plate and the mannequin, measured forces (F_x F_y F_z and F_R) and moments (M_x M_y M_z and M_R) at the hips about the principal trunk axes. Tekscan 9811 pressure measurement sensors were place over the shoulders, upper and lower back, and waist area in order to measure average pressures, peak pressures as well as average contact forces in each area. Relative displacement of payload items in the LC system were measured using up to

four Polhemus Fastrak™ magnetic sensors, which were placed on specific kit items for fighting order assessments and one in the pack for marching order assessments. The six degree of freedom movement of the described the motion of the payload and kit items relative to the mannequin during gait.

The protocol for LC Simulator testing involved: a) carefully dressing the mannequin with the test gear, b) tightening the shoulder, waist and other straps to standardized tensions based on in-line strain gauges, c) balancing the anterior/posterior moment to zero for each test condition thus simulating a balanced load, and d) collecting five repetitions of 10 seconds of data every 5 minutes at data acquisition rate of 50 Hz. The speed of LC Simulator motions was standardized at 3.5 Hz for jogging simulations and at 1.8 Hz for walking simulations. Post-processing of raw data was conducted on all outcome measures and these data were compared to a previously collected database of other packs tested under the same conditions.

Load Carriage Compliance Tester. The LC Compliance tester was designed to examine the natural stiffness of a pack suspension system and can also be used to examine the resistance of a fragmentation vest or load carriage vest to trunk flexion, lateral bending and torsion motions. The LC Compliance tester was validated against human trials and the rigidity of the system was inversely correlated ($r^2 > 0.86$) to several performance variables such as: users' comfort and ability to perform whole body and arm motions[4].

The LC Compliance tester is an articulated 50th percentile torso that is covered with Bocklite™ and bends forward and sideways at a L3/L4 level and in torsion around a L4/L5 level. Using a cable-pulley system and a preset load of 5 kg, the upper body is rotated around one axis at a time to: a) 48° of flexion, b) ±18° of lateral bending and c) ±12° of torsion.

The testing protocol involved: a) taking a baseline without a LC system in place, b) mounting an empty LC system on the Compliance tester with standardized strap tensions, c) collecting three trials of data for each condition around each axes of motion, d) subtracting the baseline resistance of the test equipment from each trial, filtering and averaging the trials, e) assigning the best fit regression equation to the data, and f) reporting the bending stiffness in Nm/deg for each axes of motion.

Part 1: Assessment of Fragmentation Vests

Introduction. The purpose of this study was to examine three designs for the fragmentation (Frag) vest both objectively and subjectively. The Frag vests under review were: the current Canadian vest (Gen-2) and two new prototypes, Gen-3A and Gen-3B. The design concept was built from the human body outward. The main differences in features between vests were: the Gen-2 had overlap junctions of front and back panels at the shoulders and a removable neck guard, the Gen-3A had side junctions and a lower profile removable collar and the Gen-3B had an asymmetric left side shoulder and side junction closure. To create a realistic and standardized testing condition, a mesh style of Tactical Vest (with a payload of 98 N) was worn over each Frag vest. This study is available from DCIEM in more detail.[5]

Methodology. To examine the dynamic responses of the three Frag vests and their impact on the user, the LC Simulator was used. The 50th percentile mannequin was programmed for 6 km/hr (3Hz) jogging. Data were taken from the relative displacement sensors, the pressure sensors, and the hip forces and moments. To examine body motion restrictions due to design, the LC Compliance tester was used to collect stiffness characteristics of the three Frag vests. To gather user discomfort information and additional factors related to mobility, test subjects completed components of the battlefield circuit and submitted individual Likkert Scale responses and focus group feedback.

Results and Discussion. Table 1 provides a summary of the rank order results for three Frag vests. There were negligible differences between Frag vests for relative kit motion and hip moments and shear forces, but the pressure system indicated high pressure points. The Gen-2 vest had local pressures of 70 kPa in the collar area because of seams and edges and the Gen-3B had over 89 kPa on the left shoulder at the closure juncture. The overlapping of the ballistic layers caused a discontinuity that exerted high pressures when the shoulder area was loaded by additional load carriage equipment. Since over 16 kPa can cause complete

cessation of blood flow to an area[6], and 90% of soldiers reported discomfort with over 20 kPa of average pressure for a 6 km march[7], then these point pressures will cause complaints and possibly injury to the skin. For peak pressures, 35 kPa was the level where soldiers would begin identifying discomfort and only the Gen-3A vest did not exceed that recommended limit for peak pressure[5]. In the human trials, subjects reported interference between specific kit items of clothing and equipment and Frag vests and occasional reports were that ballistic layers and edges were poorly positioned for comfort. In addition, the shoulder closures on the Gen-2 and Gen-3B vests were considered to be uncomfortable.

Table 1. Summary of rank order results for three fragmentation vests.

Variables	Gen-2	Gen-3A	Gen-3B	Discussion
LC Simulator Measures				
- Displacement (mm)	2	1	3	Negligible motion for all Frag vests
- Peak Pressure (kPa)	2	1	3	Collar (GenII), shoulder closure (GenIIIB)
- Forces & Moments	1	2	2	Negligible effects for all Frag vests
LC Compliance Measures				
- Forward (Nm/deg)	1	2	2	GenIIIA & GenIIIB extend down torso
- Lateral (Nm/deg)	2	1	3	Side closures reduce stiffness
- Torsion (Nm/deg)	3	1	2	GenIIIA had larger gap at waist with fastener
Human Factors				
- Subjective Reviews	3	1	2	Shoulder closures were uncomfortable One buckles on TV created a pressure point

Conclusion. In conclusion the Gen-3A Frag vest was recommended to the CTS design team with specific improvements. This phase of the research feedback was provided to DCIEM within two weeks of receiving the equipment.

Part 2: Assessment of Tactical Vests

Introduction. The purposes of this study were: 1) to evaluate the impact of wearing or not wearing a Frag vest underneath a Tactical Vest; and 2) to assess seven vest or webbing-based systems with objective measures. For this study, seven tactical assault systems were assessed: three short vests (SV1, SV2, SV3), two waist length vests (LV1, LV2), and two sets of webbing (Web1, Web2). The Gen-2 Frag vest was used for assessment of the effectiveness of the system with or without a fragmentation protective vest. As with the previous study, the objective was to provide the test results to the design team quickly, as well as uncover potential problems or compatibility issues, and make design recommendations. This study is available from DCIEM in more detail.[7]

Methodology. Only the LC Simulator was use in this study under jogging conditions comparable to 6 km/hr (3 Hz). Each tactical assault system was assessed with a payload of 7.33 kg consisting of the following kit items: one C-9 magazine, four C-7 magazines, one water canteen, two smoke grenades, two fragmentation grenades, and miscellaneous clothing. The four Fastrak™ motion sensors were placed within non-metallic casements in the C-9 magazine, the water canteen and in two C-7 magazines. The outcome measures were: a) total kit motions in x,y,z and the vectoral sum r of the motion; b) forces and moments at the hip level from the AMTI load cell; and c) peak pressure, average pressure and contact area of the Tactical Vests from the Tekscan™ pressure measurement system. In addition, each configuration was checked for compatibility both visually, in terms of geometry, conflict with the shoulder strap or waist belt and other conflicts, and in terms of battle relevant tasks such as accessibility, restriction of motion, interference and comfort.

Group data from all seven systems were submitted to a paired t-test comparison with a Bonferroni correction for multiple applications. Based on this correction, $p>0.017$ was accepted for significance.

Results and Discussion. Figure 2 is a graphic representation of the impact of wearing a fragmentation vest on all LC Simulator outcome measures. There was no statistical significance between the Frag and no Frag conditions, except for the net reaction forces and moments. Naturally, these outcome variables would be impacted by the weight of the fragmentation vest and the moment necessary to control it. The variables of total kit displacement, and peak and average pressures were not significantly affected by wearing the fragmentation vest. It would appear that both motion of the payload and skin contact pressures are unchanged by wearing a Frag vest but added weight and added heat load may affect soldier comfort or performance. This is a moot point in battle when personal safety (via evading or returning fire) is the paramount concern. However, during non-combat conditions, soldiers would have an increased physiological demand on their bodies while wearing the fragmentation vest.

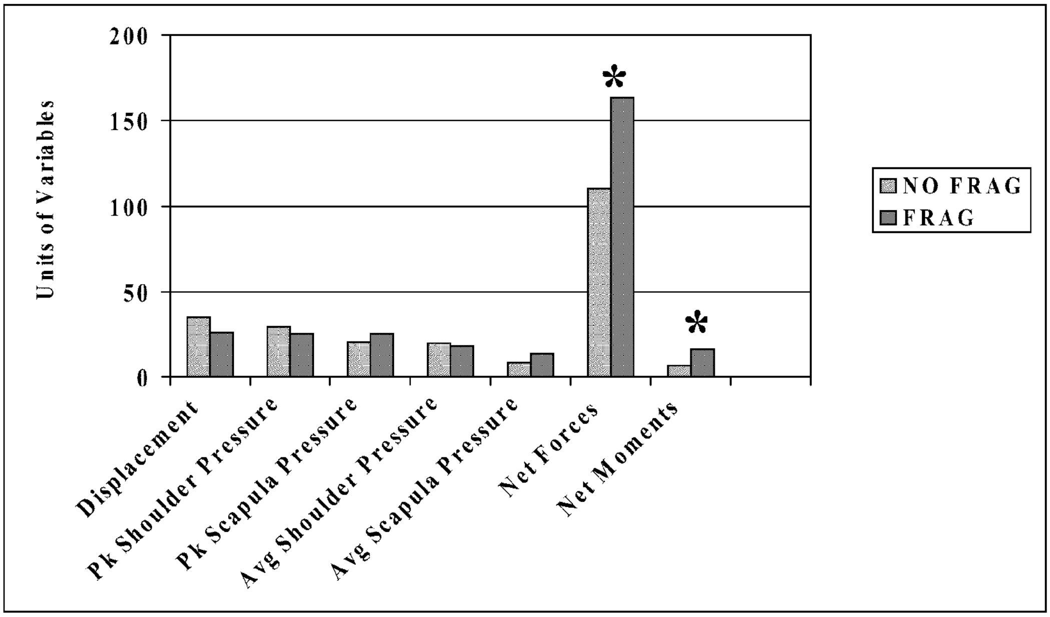

Figure 2. Effect of Wearing a Fragmentation Vest on LC Simulator Measures

The objective variables from the LC Simulator test that will be presented include net relative displacement and average pressure over the combined anterior and posterior shoulder region. Only the top two rankings will be discussed with reasons given for their ranking. The Frag/no Frag conditions were combined in the ranking except for forces and moments where there were significant differences between conditions.

Figure 3 depicts displacement of the payload relative to the mannequin for each of the seven Tactical Vests under Frag and no Frag conditions. When examining the net displacement of the kit during jogging, SV3 had a combined best score showing the least relative motion during jogging under both Frag/no Frag conditions. The second best system was LV1, but in this case the fragmentation vest served to reduce the relative motion between the kit and the mannequin. In most other cases the relative displacements of the kit items moved more on the soldier without the fragmentation vest.

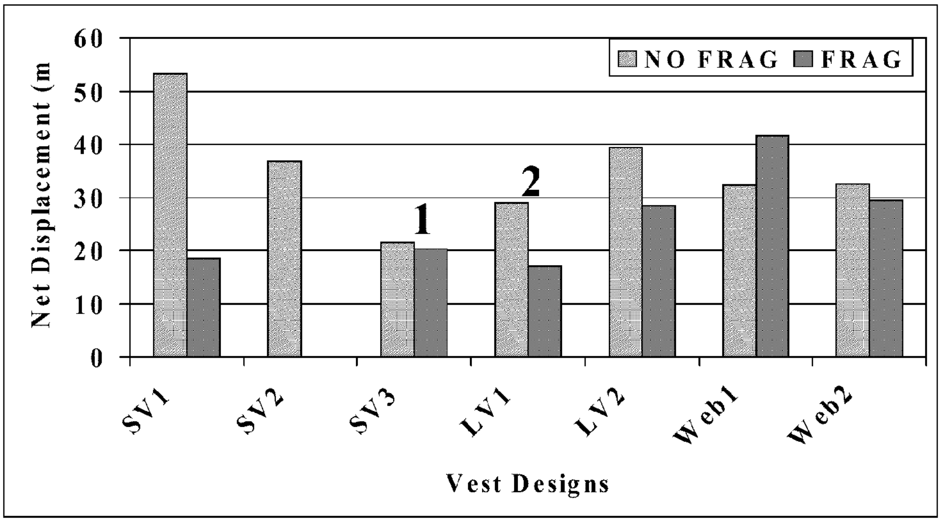

Figure 3. Effect of Tactical Vest Designs on Net Relative Kit Displacement

Figure 4 shows the average shoulder pressure when the anterior and scapular regions are combined. The top ranking systems were SV3 followed by the Web2, a webbing-based system. Maintaining a low average pressure is important since 90% of soldiers report discomfort at 20 kPa of pressure[8]. This means that only the SV3 was within recommended limits for both conditions. The importance of keeping the average shoulder pressures at a minimum in fighting and battle order is critical if one considers that the rucksack will also add to the shoulder pressure that soldiers will experience in the marching order of dress[1].

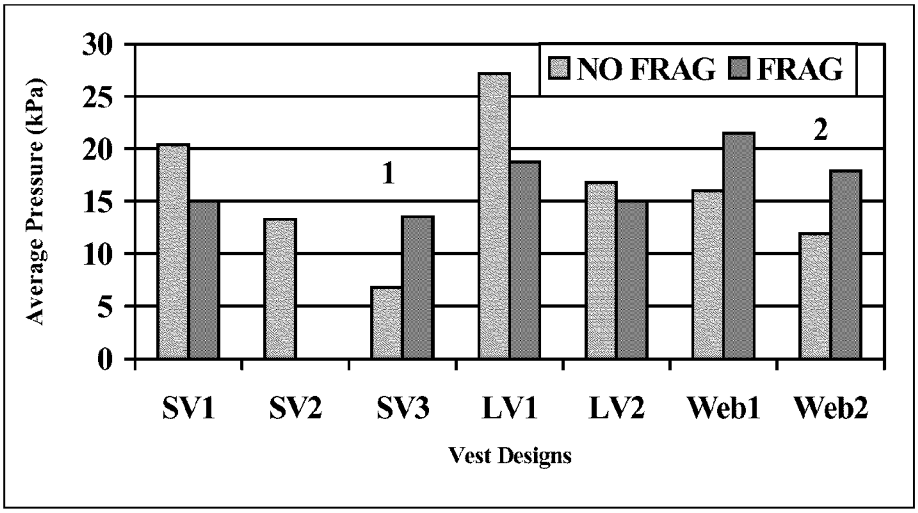

Figure 4. Effect of Tactical Vest Designs on Average Shoulder Pressure

[1] Fighting, Battle and Marching Order refers to the "order of dress" or standardized clothing & equipment carried to sustain soldiers for 8, 24 or 72 hours respectively. Fighting Order typically involves webbing or vest alone. A patrol pack or added storage pouch is added to make up Battle Order. Marching order adds the rucksack to the former dress conditions.

In terms of compatibility, the investigators observed laxity in the attachment of various kit items, specific pressure hotspots of concern with each fighting order system, and interference between specific kit items when the fragmentation vest was worn. In terms of human trials, results confirmed that there were similar hotspots to those identified on the LC Simulator; soldiers reported LC vest systems that had excessive looseness of the kit, as well as difficulty making certain movements during some of the battle order tasks.

Conclusions. In conclusion, based on the objective data, and limited human factors data, the SV3 vest was recommended to the Canadian Forces under the following conditions: 1) that SV3 be designed with protected spaces for the shoulder straps, waist belt and back support area to receive the backpack; 2) that shoulder stitch locations and a padded shoulder design be implemented to reduce shoulder pressures; 3) that the conflict be removed between the SV3 vest and C-9 magazine and 4) that the Gen-2 fragmentation vest collar and ballistic material ridges be modified to overcome problems relating to comfort. These changes were implemented before the team continued with military focus groups and field trials in order to get feedback on final design features. After these trials, a modified SV3 was renamed and became the Tactical Vest for the final system. Only three weeks of objective testing were needed to give the DCIEM design team initial feedback on the Tactical Vest study.

Part 3: Evaluation of Rucksack Designs

Introduction. As part of the overall design process, various iterations of the rucksack were developed and tested by both human trials and standardized objective measures. Prior to commencing the study, the designer had requested that several commercial packs be assessed by the Queen's Ergonomics Research Group biomechanical testing centre. The database of backpacks was, therefore, advanced to include both civilian and military systems. In total, 17 systems were in the database prior to comparative studies with prototypes of the CTS rucksack design. In previous steps, the design team had identified protected spaces on the SV3, now called the Tactical Vest (TV), that were necessary to accept the shoulder straps, waist belt and back support area for the backpack. The purpose of this study was to assess three designs of the CTS rucksack with objective measures and to recommend solutions to design problems prior to development of the next iteration. This information is also available in greater detail in a DCIEM report.[9] There were also sub-studies to examine specific design questions such as, the optimum location for the lower shoulder strap attachment point and the effect of the addition of lateral rods into the suspension system. These studies have been reported by Reid et al.[10,11].

Methodology. The three prototypes, models K, M and F, designed by Ostrom Outdoors Inc. of Nolalu, Ontario were sent to Queen's for appraisal. Model K was the "keep it simple" design, the Model M was the "modular system" and Model F was the final model that had features from both of the previous versions. A combat shirt and the previously tested Tactical Vest (TV) were worn under the packs during all tests.

Prior to testing, the mass properties of the system were taken that included the mass of the pack plus payload, its' centre of gravity and the physical dimensions. The systems were carefully adjusted to suit the 50^{th} percentile male mannequin size and with standardized strap conditions of 60 N per shoulder strap, 50 N on the waist belt, 100 N per hip stabilizer strap, 60 N per load lifter strap and 60 N on the sternum strap. The standardized test protocol as implemented for both the LC Simulator and LC Compliance Tester. Visual inspections for compatibility and brief human trials were also conducted. The three models, K, M and F were compared to one another and to the pooled database. Each prototype was compared to the mean of the data pool for each correlated variable and the lower 10% of inferior packs and upper 10% or superior packs.

Results and Discussion. Only the most relevant correlated results will be compared in this paper but greater details are available within the DCIEM technical reports[12,13,14]. Figure 5a shows the stiffness of the suspension systems in Nm/deg in flexion, lateral bending and torsion as taken from the LC Compliance tester. All stiffness measures were highly correlated to mobility, load control and comfort dealing with load transfer. Although the prototype systems were not considered superior, they were not substantially handicapped by the inclusion of lateral rods in the suspension system. This means that the pack frames'

resistance to gait and mobility motions were above average around all three axes. The poorest performers in pack frame stiffness about all three axes were some military systems and external frame packs.

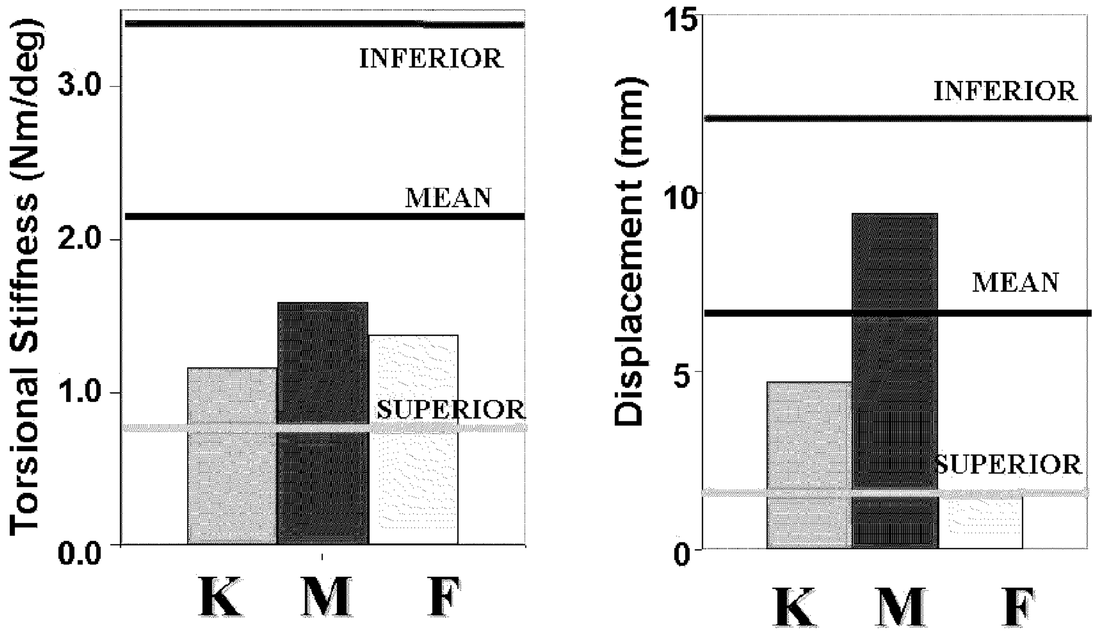

Figure 5a. Suspension Stiffness from the LC Compliance Tester.
Figure 5b. Relative Pack Displacement from LC Simulator

Figure 5b displays the resultant relative displacement in millimeters between the pack and person for the K, M and F systems. This variable had been shown to be related to hip discomfort, probably due to transfer of impact loads to the lumbar pad and hip region of the waist belt[8]. Minimal relative pack motion is characteristic of a stiff suspension system, a factor that was evident by the difference from the modular M pack to the Model F. Load control is improved with a stiff suspension system because it will move in response to the soldier's trunk motion. In this regard, Model F was superior as it fell within the top 10% of packs in the database.

Figure 6a is a selection of one average force variable (Fz) as a representative of the average force and moment data from the load cell at the hips. These outcome variables have been shown to be correlated to overall mobility, balance and overall comfort. The model F design had a very stiff suspension system that transferred higher vertical loads to the body. As model F induced higher vertical reaction loads than other packs in the database, it was ranked as inferior in transmission of vertical (Fz) forces through the spinal column but it was superior in side to side (Fy, Mx) control. It is easy to see the logic of maintaining small side to side forces and moments for good pack control. However, the interpretation that higher average Fz forces for backpacks are problematic may be incorrect, given that basic research studies have shown the tissue tolerance limits for compression of a straight spinal column to be higher than other axes and hence may be able to withstand high forces without injury[15]. The F model pack was superior in My flexion/extension moment that would keep spinal shearing forces to a minimum[14]. If the compressive Fz forces through the spinal column are not a problem, for the backpack wearer, then the cause of soldier discomfort scores in the current database needs further examination. Further human studies would be helpful to understand and explain this relationship.

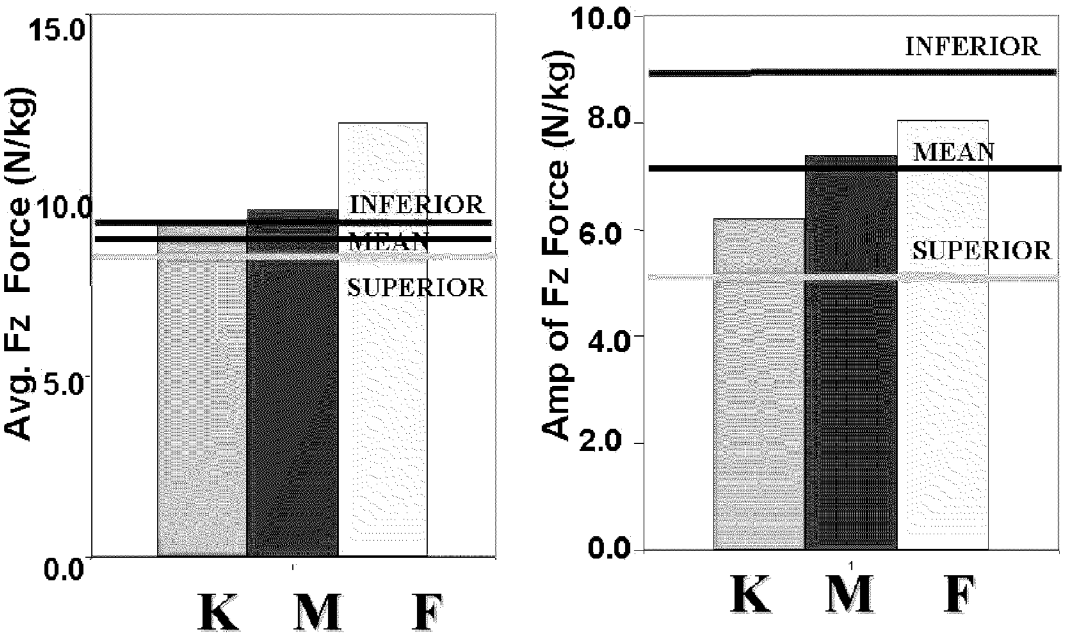

Figure 6a. Average Force (Fz) from the LC Simulator.
Figure 6b. Amplitude of Force (Fz) from the LC Simulator.

Figure 6b is a representation of force and moment amplitudes and of the three CTS prototypes in comparison to database systems. The amplitudes of x, y, z moments in Nm/kg and the z and r forces in N/kg were correlated to load control such as balance, mobility, and maneuverability[8]. The three prototypes were consistently below average or inferior indicating that there was a substantial dynamic component experienced by the hips. This was not reflected in the shoulder pressure average profiles nor in the relative displacement of the pack, indicating that the pack suspension system was absorbing most of the oscillating forces and moments. Kram[17] proposed that that a dynamic suspension system could be helpful to return mechanical energy to the body through use of bamboo poles. In a sub-study that was designed to examine the effects of lateral rods in the suspension system, Reid et al.[9] found reduced vertical compressive force Fz and increased extension moment My at L1 with the use of these rods. If these amplitudes can be controlled, then it is possible that a tunable dynamic suspension system could be created. Further research is needed to investigate this theory.

Figure 7a is the average anterior shoulder pressure and Figure 7b is the peak anterior shoulder pressure summarizing the pressure profiles experienced by soldiers wearing the prototype systems. From previous studies collated into the database, five shoulder pressure measures and two lumbar pressure measures were related to soldier reports of discomfort, especially in the posterior hip and neck regions, and a reduced ability to doff the pack[8]. In all contact pressure variable studies, the three systems ranked in the superior category. During the CTS design cycle, there were two sub-studies that may have helped generate this positive result. In one study the optimum location for the lower shoulder strap attachment point was selected to reduce lumbar shear and minimize peak loading of the anterior shoulder/axilla region[10]. In the second study, three types of strap shapes were investigated to reduce the contact pressure profiles[16]. In addition, the meticulous care devoted to integrating the strap configurations with the straps of the TV may also have contributed to prototypes' superior performance.

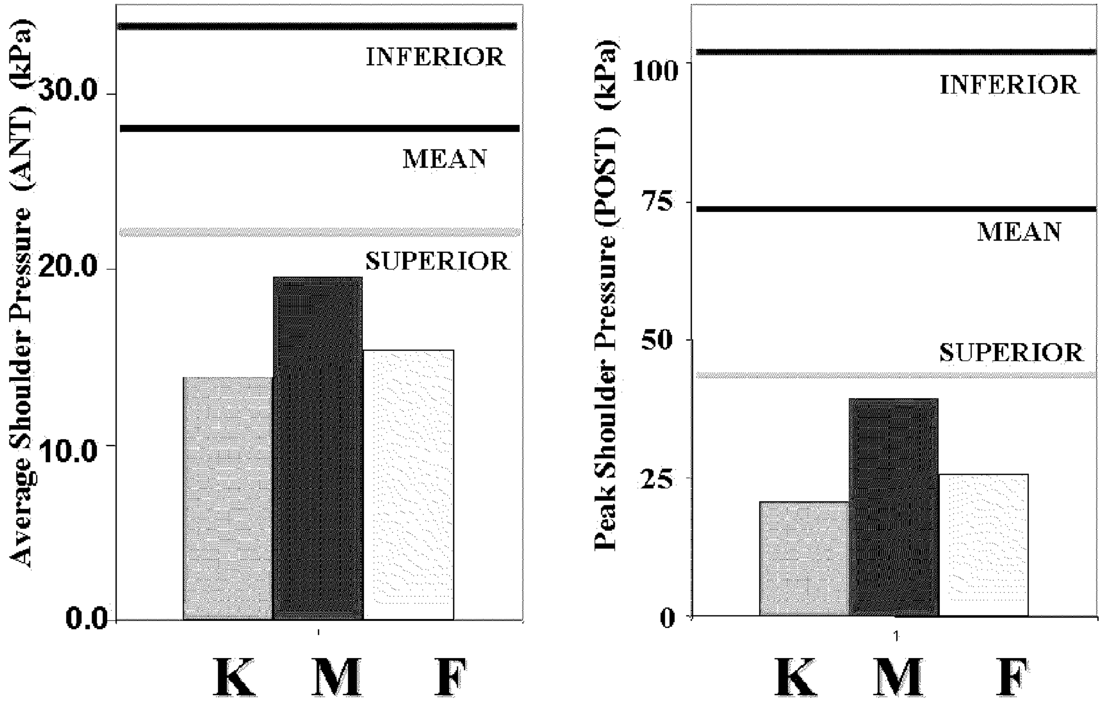

Figure 7a. Average Anterior Shoulder Pressure from LC Simulator.
Figure 7b. Peak Posterior Shoulder Pressure from LC Simulator.

Conclusions. In summary, the model F was a composite of features from the previous prototypes. It was designed to have one large storage compartment with two openings (top and front) and a number of detachable storage pouches for modularity. The CTS pack system had load-lifter straps, sternum and hip stabilizer straps. The suspension system was an internal frame system with lateral rods thus giving some adjustable dynamic characteristics. The internal frame pack and the shorter TV allowed better maneuverability and load control. The pack integrated well with the TV because specific interference problems were identified earlier in the process and corrected.

When the results were compared to the benchmark pool, the F model fell into the superior category on 48% of the variables, above average on 24%, below average on 14% and inferior on 14% of the variables. The pack was in the lowest 10% or inferior on amplitudes of forces and moments at the level of the hips. These amplitudes were being absorbed by the suspension system as neither the pack motion nor pressure at the shoulders were increased as a result of these increased amplitudes. Further human trials are needed to evaluate whether larger amplitudes of force and moments are problematic for the wearer.

All of these variables were validated against soldier input on wearing the LC systems [1, 8]. In comparison to proposed objective standards, the F model had less that 8 mm of absolute relative motion during walking and lower than 20 kPa of average pressure at the skin contact surface areas. Peak pressures were under the recommended 35 kPa with the highest peak pressure merely 27 kPa while carrying a 28.67 kg testing load. The final F model had good control in the relative pack to person motions, average suspension system stiffness, low average and peak pressures in the anterior and posterior shoulder regions, average forces and reaction moments but higher amplitudes of force and moments at the level of the hips. Overall this LC system would be a benchmark of standards that can be attained in future systems.

Overall Conclusions and Recommendations

Based on objective biomechanical testing, the F model was above average or superior to other LC systems in the database. It was concluded that this system should go forward to soldier field trials. It was also concluded that the objective assessment tools were cost and time effective and that they could provide designers with important feedback on the design characteristics of the system. Each design iteration would be tested and feedback given with two weeks. However, this scientific testing cannot replace human trials for critical design evaluations, especially in relation to pack features and functionality.

The new F model was recommended for field trials and was subsequently tested by many soldiers representing a range of military units. Since that time subtle design changes have been made in the CTS system more due to functionality than biomechanical performance. It is recommended that the final system be evaluated at Queen's and treated as the new Canadian benchmark standard since some packs in the database are poorer than current 'state of the art' systems.

Several concepts and concerns still need to be addressed in future testing. For example, it is not known if dynamic suspension systems will improve the overall performance of a LC system. As well, basic scientific data need to be collected on acceptable skin contact pressures to determine maximum tissue tolerance limits for military procurement guidelines.

Acknowledgements

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